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TRANSDUCER DEGRADATION AND HIGH AMPLITUDE BEHAVIOR OF BROADBAND PIEZOELECTRIC STACK TRANSDUCER FOR VIBROTHERMOGRAPHY

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ABSTRACT. Vibrothermography, also known as Sonic IR and Thermosonics, is an NDE technique for finding cracks and flaws based on vibration-induced frictional rubbing of unbonded surfaces. Vibration is usually generated by an ultrasonic welder or a broadband piezoelectric stack transducer which transduces electrical energy into mechanical vibrations. Defect detection in vibrothermography depends on specimen vibration, which in turn is proportional to velocity spectrum (V_{oc}) of the transducer (with sufficient coupling). A long standing problem has been generation of repeatable specimen vibrations. The broadband piezoelectric stack transducers give much better trigger-to-trigger repeatability than the welder system. Even with the broadband piezostack, at sufficiently high excitation voltages, the transducer behavior becomes non linear and less repeatable. Also, as the transducer degrades over time, its V_{oc} changes significantly. We investigate the reasons for this non linear behavior and present experimental results on the effects of excitation voltage and transducer degradation on V_{oc}. Using these results, we suggest how to improve the repeatability of vibration generation and to enhance the longevity of the transducer.

Keywords: Vibrothermography, Piezoelectric Actuator, LTI Twoport, Sonic IR
PACS: 43.20.Ks, 43.25.Ba, 43.38.Fx, 43.40.Le, 43.60.Hj

INTRODUCTION

In Vibrothermography, the specimen is excited with a transducer and the frictional rubbing between defect surfaces (e.g., cracks, delaminations) generates heat which is imaged by an infrared camera. The usual choice of excitation source is an ultrasonic welder or a broadband piezoelectric transducer. Because of the large bandwidth of the broadband transducer, it can be tuned electrically to excite the specimen at natural resonances to achieve higher vibrational amplitudes[1]. By modeling the transducer, one can predict whether it is suitable for the given inspection. The important parameters of transducer behavior are its mobility and open circuit velocity. The small signal analysis of broadband piezoelectric transducer had been reported in [2]. We showed that with adequate coupling between the transducer and specimen, the primary transducer parameter that governs the specimen motion is the 'Transducer Open circuit velocity (V_{oc})', the velocity of transducer tip when no specimen is attached to it.

In this paper, we analyse the high amplitude behavior of the broad band piezoelectric transducer. We show how the inherent nonlinearity of the PZT (Lead Zirconate Titanate) ma-

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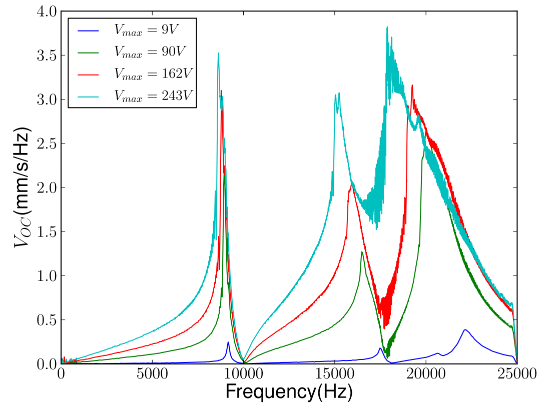


FIGURE 1. Open circuit velocity of the transducer PM1620 for different excitation voltages. As the excitation voltage increases, the higher order resonances shift towards lower frequencies. The legend in the figure shows the maximum AC voltage applied across the transducer. At the 236V excitation voltage, the magnitude of harmonics is comparable to that of the fundamental, which as a result distorts the spectrum.

terial affects the transducer velocity spectrum as the excitation amplitude increases. At sufficiently high excitation voltages and frequencies, the built in preload force in the transducer becomes inadequate to hold the stack in compression. We show that when this happens, the transducer behavior becomes more nonlinear and the stack comes under risk of early damage. We also report experimental results on how the transducer velocity spectrum (V_{oc}) changes with usage of the transducer.

TRANSDUCER HIGH AMPLITUDE BEHAVIOR AND EFFECT OF PRELOAD

The transducing element inside a broadband transducers is a stack of PZT (Lead Zirconate Titanate) discs. PZT is inherently nonlinear and its nonlinearity becomes more pronounced at high voltage excitation, thus making the overall transducer behavior nonlinear[4]. The onset of nonlinearity is marked by the increasing amplitude of higher order harmonics and the dependence of transducer's resonance frequencies on velocity amplitude. As a result, the higher order transducer resonances steadily shift towards lower frequencies with increasing excitation amplitude. Fig. 1 shows this phenomenon. In this figure, the 23kHz resonance frequency at 16V excitation voltage has shifted to around 18.5kHz at 236V peak to peak Voltage. This nonlinearity makes the transducer behavior less repeatable.

The high power broadband piezoelectric transducers have a built in mechanical preload. The reason for this preload is that the piezo ceramics can withstand large compressional forces but limited tensile forces. If the forces on the stack exceeds its tensile strength, damage to the stack is likely to occur. The mechanical preload prevents this and keeps the stack under compression. The forces on the stack are:

1. Inertial force exerted by the vibrating transducer tip, $F_{tip} = m_{tip}a$
2. Compressive preload force, $F_{preload} = k_{spring}x$

where m_{tip} is the mass of the transducer tip, a is the acceleration of the tip, k_{spring} is the stiffness of preload spring and x is the tip displacement. The net force on the stack should always be compressive. However, at sufficiently high amplitude excitation at the transducer resonance frequencies, the preload force is not sufficient to compensate the inertial tip forces.

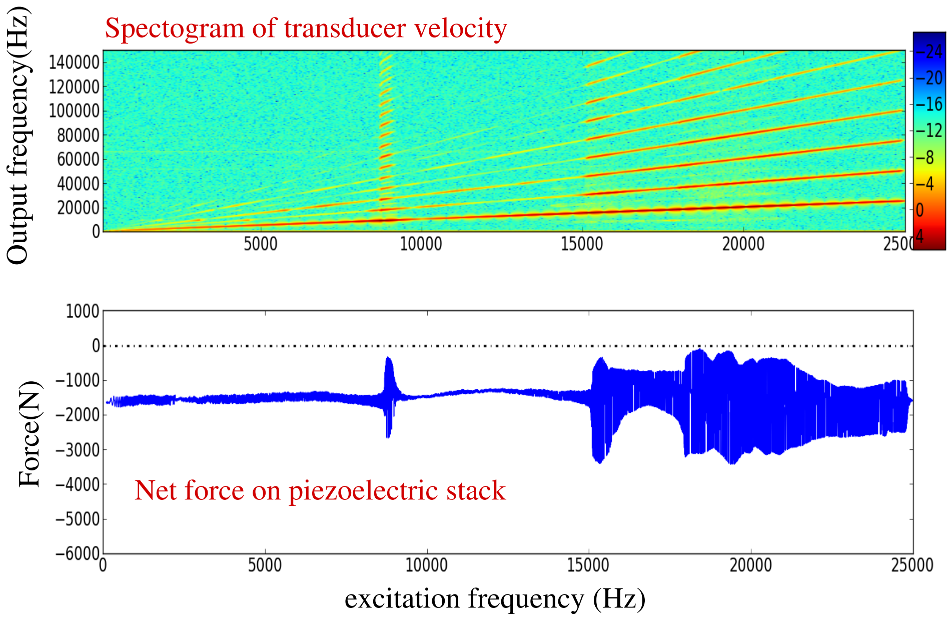


FIGURE 2. Spectogram of transducer open circuit velocity and the net force on transducer stack. The top plot shows the output freuqency content for a frequency sweep excitation. The bottom plot shows the net force on the stack for the same frequency sweep excitation. The net force is compressive and the spectrum has harmonics which come from inherent nonlinearity of the transducer.

When this happens, the stack undergoes tension and the tip can break free and collide with stack causing damage to the transducer.

To understand the effect of preload on the transducer, we plotted the spectogram of the open circuit velocity. A Spectogram is a time-frequency representation of a signal[3]. We represent the input frequency instead of time, since, for a frequency sweep excitation, the input frequency is a known linear function of time. The top plot of fig. 2 shows the spectogram of the transducer open circuit velocity. In the spectogram, the horizontal axis is the input excitation frequency (for a frequency sweep excitation) and the vertical axis is the frequency in the output velocity spectrum. The colorbar (intensity) represents the spectral density. The bottom plot of fig. 2 shows the force on the stack versus the input excitation frequency. In this plot, the net force is compressive (less than zero) at all excited frequencies and the spectogram intensity has peaks only at higher order harmonics apart from the fundamental component. The harmonics are primarily the manifestation of the inherent material nonlinearity as seen in Fig 1. However, this is not the case when the net force becomes tensile (greater than zero). Fig 3 shows the velocity spectogram and net force at a higher excitation amplitude. The net force on the stack becomes positive at 17 kHz. At this frequency, the spectogram intensity has peaks not only at the fundamental (17kHz) and harmonics (multiples of 17kHz), but also at the sub-harmonic frequencies and the harmonics of sub-harmonics (8.5kHz, 25.5kHz etc). It means that when the piezoelectric stack of the transducer undergoes dynamic tensile forces, sub-harmonics as well as harmonics appear in the open circuit velocity. The appearance of sub-harmonics in the spectrum indicate that the preload force is not sufficient to keep the stack under compression. If the transducer is used for longer periods under this condition, the risk of damage to the stack increases.

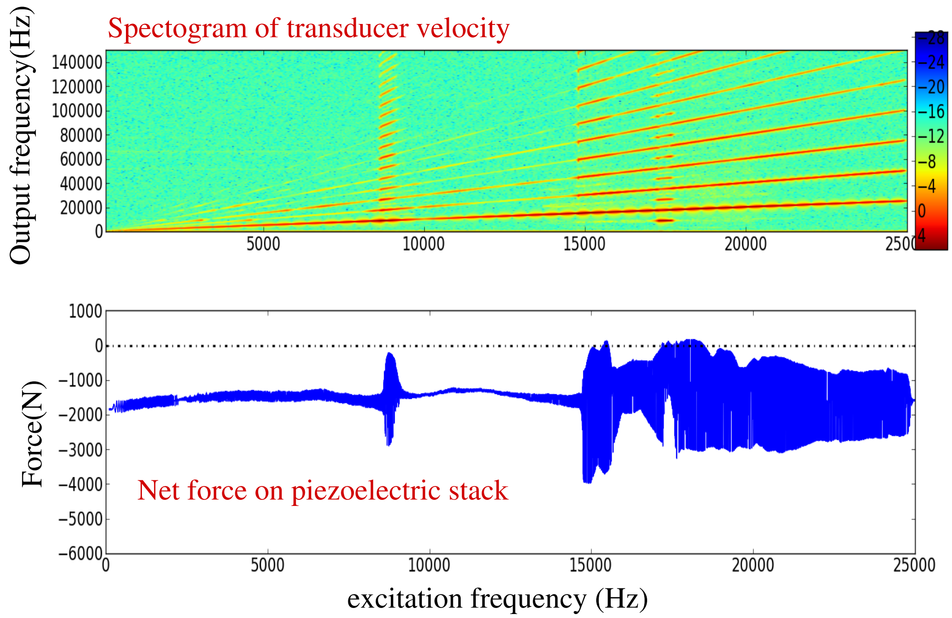


FIGURE 3. Spectogram of transducer open circuit velocity and the net force on transducer stack. The top plot shows the output freuqency content for a frequency sweep excitation. The bottom plot shows the net force on the stack for the same frequency sweep excitation. When the net force on the stack becomes tensile, sub harmonics start to appear in the spectrum as well apart from the harmonics.

DEGRADATION OF TRANSDUCER VELOCITY SPECTRUM

The stress levels achieved in Vibrothermography using a broadband transducer degrade over time and usage. we used a PI2533 (manufacturer: Physik Instrumente Inc, Stack length: 33mm, Stack diameter: 25mm) transducer to investigate its long term reliability. We triggered the transducer periodically without attaching a specimen to its tip and monitored the open circuit velocity(V_{oc}) after each trigger. The transducer was allowed to cool between successive triggers so that the effect of the piezo stack heating up (due to prolonged high amplitude excitations) on the test is minimized. To keep track of how the overall spectrum of transducer changes as it degrades, we excited the transducer with a low amplitude frequency sweep (from 100 Hz to 20 Khz at 17V peak to peak voltage) periodically after every 10 bursts and a high amplitude frequency sweep (from 100 Hz to 20 Khz at 175V peak to peak voltage) after every 100 low amplitude sweeps and saved the velocity waveforms after each trigger. The test was stopped after a total of 6397 triggers (5800 tone bursts, 585 low amplitude sweeps and 12 high amplitude sweeps).

The data sets for burst excitation, low amplitude sweep and high amplitude sweep were analyzed separately. The velocity spectrum for all the sweep tests has been calculated from the data. Fig. 4 shows the magnitude of small signal spectrum of the transducer at various stages of testing. The spectrum of the tranducer remained almost unchanged upto a frequency of about 8 Khz. At frequencies above 8 Khz, even though the magnitude of the spectrum did not follow a clear trend, the resonance frequencies have shifted across all the 6400 triggers.

Fig. 5(a) shows the plots of the transducer high amplitude spectrum as the test progressed. We could not observe any obvious trends in the original spectrum because of the interference between fundamental and harmonic components as seen in fig. 5(a). So, we separated the harmonics and the fundamental component from the original spectrum and plotted

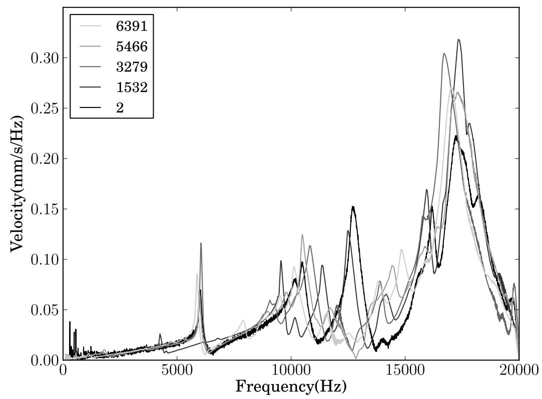
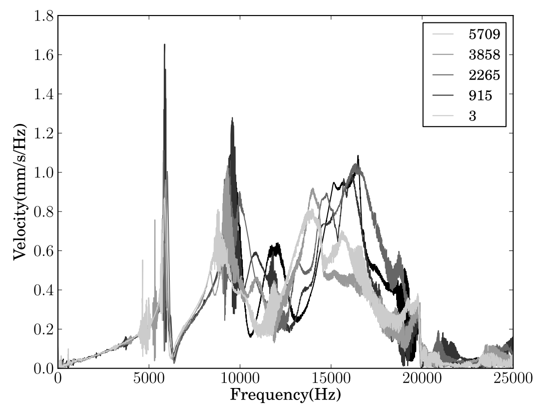
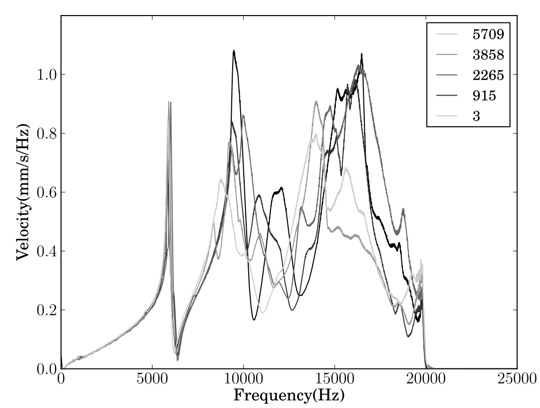


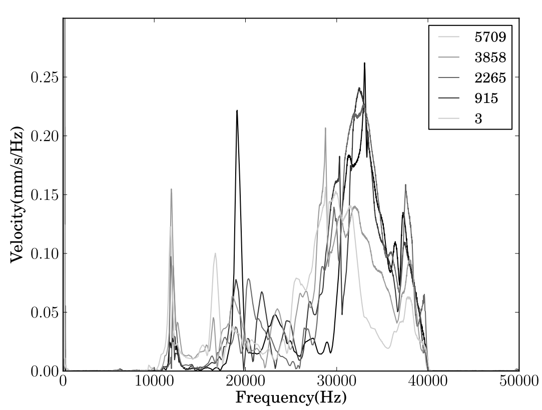
FIGURE 4. Small signal spectrum of the transducer PI2533 after 2, 1532, 3279, 5466 and 6391 triggers in increasing order of grayscale. The higher resonance frequencies are shifted across the triggers, but the magnitude of the spectrum did not change significantly.



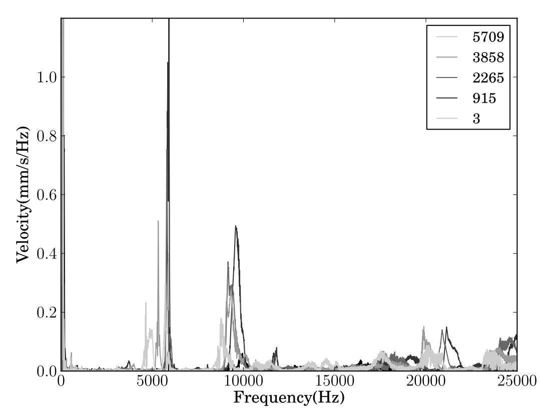
(a) raw spectrum



(b) fundamental component



(c) second harmonic



(d) residuals

FIGURE 5. High amplitude spectrum of the transducer PI2533 calculated after 3, 915, 2265, 3878 and 5709 triggers with decreasing gray scale levels. The plot on the top left shows the complete raw spectrum without any filtering. The plot on top right shows the fundamental component of the spectrum and the plot on bottom left shows the 2nd harmonic. The plot on bottom right shows the residuals after subtracting the fundamental and second harmonic from the raw spectrum. Legend shows the trigger number of the corresponding test.

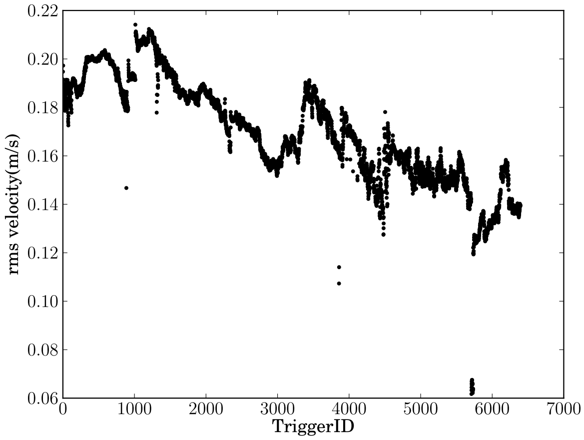


FIGURE 6. rms value of velocity of all the tone burst excitations of the tranducer PI2533.

them separately as shown in fig. 5(b)-5(d). The fundamental component of the spectrum again remained almost unchanged upto about 8 Khz. At higher frequencies, however, the spectrum magnitude has reduced siginificantly across all the 6400 triggers. Even the resonance frequencies have shifted considerably as seen in fig. 5(b). For instance, the resonance frequency at 18kHz at trigger no. 3 moved to 14kHz at trigger no. 5709. Also, the originally wider high frequency resonance peaks started to shrink in width. We hypothesize that this might be an indication of the piezo stack degrading, because when the stack degrades or cracks, its stiffness changes and therefore the resonances change too.

Finally, the root mean square (RMS) value of the velocity waveforms for burst excitation was calculated as a measure of the velocity amplitude. This value is plotted with the trigger ID as shown in fig. 6. The overall RMS value of the velocity decreased by about 20% over the 6400 triggers. The fact that the resonance frequencies shifted around as the test progressed (as seen in fig. 5(a)) might be an explanation for the local variations in the velocity. But clearly, there is a decrease in excitation effectiveness as the transducer degrades.

CONCLUSION

Transducer plays a critical role for defect detection in Vibrothermography. PZT is inherently nonlinear and the nonlinear behavior becomes pronounced at high amplitudes. The transducer resonance frequencies become lower as the excitation amplitude increases. Also, the magnitude of higher order harmonics becomes significant compared to the fundamental. When the preload force is not adequate to keep the stack under compression, the transducer tip breaks contact and collides with the stack. This leads to sub-harmonic generation in the velocity spectrum. The transducer spectrum changes significantly with time and usage of the transducer. The magnitude and resonances of low amplitude spectrum do not change significantly but the magnitude of high amplitude spectrum deteriorates and resonance frequencies decrease as the transducer ages.

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